

Steam Enhanced Remediation Research for DNAPL in Fractured Rock Loring Air Force Base, Limestone, Maine



Steam Enhanced Remediation Research for DNAPL in Fractured Rock Loring Air Force Base, Limestone, Maine

Eva Davis
U.S. Environmental Protection Agency
Ada, Oklahoma 74820

Naji Akladiss & Rob Hoey
Maine Department of Environmental Protection
Augusta, Maine 04333

Bill Brandon & Mike Nalipinski
Region 1
U.S. Environmental Protection Agency
Boston, Massachusetts 02114

Steve Carroll & Gorm Heron
SteamTech Environmental Services, Inc.
Bakersfield, California 93308

Kent Novakowski
Queens University
Kingston, Ontario, Canada K7L3N6

Kent Udell
University of California, Berkeley
Berkeley, California 94720

State of Maine
Department of Environmental Protection
Augusta, Maine 04333

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Notice

The U.S. Environmental Protection Agency through its Office of Research and Development, Maine Department of Environmental Protection, United States Air Force, and SteamTech Environmental Services, Inc., funded, managed, and collaborated in the research described here. It has been subjected to the Agency's peer and administrative review and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

All research projects making conclusions or recommendations based on environmental data and funded all or in part by the U.S. Environmental Protection Agency are required to participate in the Agency Quality Assurance Program. This project was conducted under an approved Quality Assurance Project Plan. Information on the plan and documentation of the quality assurance activities and results are available from the lead author.

Preface

The Maine Department of Environmental Protection (MEDEP) understands that cleanup of fractured bedrock aquifers is difficult, expensive, and in many cases technically impracticable, but we still find technical impracticability difficult to accept. Therefore, when reasonable arguments arose against a technical impracticability waiver for the Quarry, MEDEP was anxious to find a technology that would reduce the mass of contaminant trapped in the bedrock. MEDEP conceived the Quarry project as a modest effort, meant to try innovative methods of mass reduction on a limited budget over a limited time. The Quarry location seemed ideal for trying out new technologies – remote, in a harsh climate, and far from receptors. As it turned out, the modest effort was nurtured by the expertise and resources of many agencies and individuals. I am grateful for their efforts and grateful I got the chance to work with them.

MEDEP would like to acknowledge the following parties who were crucial to the completion of the project:

Funding was provided by U.S. EPA, through its Superfund Innovative Technology Evaluation (SITE) program. Ms. Annette Gatchett of EPA (SITE program) provided excellent management skills in providing funding and oversight of the steam injection program.

Special thanks to Dr. Eva Davis of U.S. EPA for assuming the role of technical lead for the entire steam injection project. Dr. Davis' invaluable contribution to the project was the key to our success. She maintained the project on track, resolved many of the technical problems and tracked all project data. Dr. Davis was a major contributor to this report.

Mr. Paul Depercin of U.S. EPA (SITE program) provided a great deal of support in the field as well as contract management.

Mike Nalipinski and Bill Brandon of EPA Region I have provided the team with outstanding support. Mr. Nalipinski invested more than seven years into the Loring remediation; his input in to the program helped resolve many obstacles we encountered. Mr. Brandon's technical expertise in the field of structural geology and his knowledge of the site geology helped the team in the decision making process.

Mr. David Strainge of the U.S. Air Force provided crucial funding and project oversight. Mr. Strainge has been an invaluable resource to the Air Force and the people of Maine in the ten plus years since the base went Base Realignment and Closure (BRAC).

Many thanks to Rob Hoey and Robert Sypitkowski of the MEDEP for their contribution to the steam project in the area of geology and engineering. Mr. Hoey and Mr. Sypitkowski spent countless hours working on the project. Mr. Hoey was a great instrument in building a site map, the collection of ground water samples, and data processing.

SteamTech Environmental Services, Inc., contributed funding and technical expertise. SteamTech contributed a great deal to the success of the research project. Hank Sowers, Dr. Gorm Heron, Dr. Steve Carroll, and Gregg Crisp were great instruments in the design and operation of the steam injection at the Quarry.

This project would not be possible without the invaluable contribution of Dr. Kent Udell of the University of California at Berkeley and Dr. Kent Novakowski of Queen's University, Ontario, Canada.

EPA's Office of Environmental Measurement and Evaluation (Region I) made significant contributions to the success of the project in terms of technical expertise in vapor sampling, analysis of vapor samples, and validation of laboratory data.

Many thanks to the Maine Department of Human Services Laboratory for their efforts in analyzing aqueous phase samples and for providing the analytical data in a timely manner.



Naji Akladiss, P.E.
Loring Quarry Steam Injection Research Project Manager
Maine Department of Environmental Protection

Acknowledgments

Loring Quarry Steam Injection Research Project Team

U.S. Environmental Protection Agency:

Annette Gatchett, Associate Director for Technology,

ORD/NRMRL – Cincinnati, Ohio

Paul de Percin, SITE Project Manager, ORD/NRMRL – Cincinnati, Ohio

Dr. Eva Davis, Technical Lead, ORD/NRMRL – Ada, Oklahoma

Mike Nalipinski – Remedial Project Manager, Region 1

Bill Brandon – Geologist, Region 1

Maine Department of Environmental Protection:

Naji Akladiss, P.E., Project Manager

Rob Hoey, C.G., Geologist

Robert Sypitkowski, P.E., Engineer

SteamTech Environmental Services, Inc.:

Hank Sowers, CEO

Dr. Gorm Heron, Project Engineer

Dr. Steve Carroll, Project Geologist

Gregg Crisp, Field Manager

Air Force Base Conversion Agency:

David Strainge, Engineer

Experts from Academia:

Dr. Kent Novakowski, Queens University

Dr. Kent Udell, University of California - Berkeley

Executive Summary

This report details a research project on Steam Enhanced Remediation (SER) for the recovery of volatile organic contaminants (VOCs) from fracture limestone that was carried out at an abandoned quarry at the former Loring Air Force Base (AFB) in Limestone, Maine. The project was carried out by United States Environmental Protection Agency (U.S. EPA) Office of Research and Development (ORD) National Risk Management Research Laboratory (NRMRL), U.S. EPA Region I, Maine Department of Environmental Protection (MEDEP), SteamTech Environmental Services, Inc., the United States Air Force (USAF), and experts from academia on characterization of fractured rock and steam injection remediation. U.S. EPA's Superfund Innovative Technology Evaluation (SITE) program participated in this research project to evaluate the SER technology in the fractured rock setting.

Loring AFB was added to the Superfund National Priorities List in 1990, and the Quarry was one of more than 50 sites on base that were addressed. The Quarry had historically been used for the disposal of wastes from construction, industrial, and maintenance activities at the base, and during remedial activities in the 1990s, approximately 450 drums were removed. Subsequent investigations showed that both chlorinated organics and fuel-related compounds were present in the ground water beneath the Quarry. Tetrachloroethylene (PCE) was detected at concentrations indicative of the presence of Dense Non-Aqueous Phase Liquids (DNAPL). The Record of Decision (ROD), signed in 1999, recognized that it was currently impractical to restore ground water in fractured rock to drinking water standards. However, an agreement was made between the USAF, MEDEP, and EPA Region I to use the Quarry to conduct a research project to further the development of remediation technologies in fractured rock, and with the hope of recovering contaminant mass to reduce the timeframe for natural attenuation of the remaining contaminants. In addition, the regulatory agencies hoped to develop guidance on characterization techniques for fractured rock. A Request for Proposals (RFP) for technologies to be tested at the site was issued in 2001, and SER was chosen from the proposals received.

With a technology and a vendor chosen, additional technology specific objectives for the research project were developed, which included determining if SER could: 1) heat the target area for remediation, 2) enhance contaminant recovery, and 3) reduce contaminant concentrations in the rock and ground water. Secondary objectives included determining if contaminants were mobilized outside of the treatment area, documenting the ability of SteamTech's effluent treatment systems to meet discharge requirements, determining operating parameters for fractured rock, and documenting costs.

Characterization activities were initiated in 2001 with the installation of process boreholes based on the agreed on treatment area and the preliminary design of the treatment system. These borings were cored and logged, and rock chip samples were collected from fracture surfaces for determination of contaminant concentrations. Additional characterization activities included discrete interval transmissivity testing and ground water sampling, conventional borehole geophysical and acoustic televiewer (ATV) logging, and interconnectivity testing. Based on the results of all the characterization activities and an updated conceptual site model (CSM), the steam injection and extraction system was revised to include steam injection at the eastern side of the target area, with extraction along the center line and the western side of the target area.

Construction of the system was initiated in August 2002, and the extraction system starting operation on August 30. Steam injection was initiated on September 1, and continued until November 19, when funding for the project ran out. Extraction was terminated on November 26. Throughout operations, EPA's SITE program collected effluent vapor and water samples to document the contaminant recovery rate and amount of contaminants recovered. SteamTech collected temperature data using 22 thermocouple strings, and documented changes in subsurface resistivity caused by temperature increases or by steam replacing water in the fractures using electrical resistance tomography (ERT).

Early in operations, it became apparent that steam injection rates were much lower than anticipated due to low transmissivities in the injection intervals and sparsely spaced fractures. In an attempt to inject more steam and increase the rate of heating, three extraction wells were converted to injection wells during operations. Although this significantly increased the amount of steam being injected, the amount of energy that could be injected during the limited-time project was still low, and the entire target zone for treatment could not be heated. The highest recorded temperature away from the injection wells was approximately 50°C, which was recorded approximately 4.5 meters (15 feet) from the nearest injection well. ERT was found to be capable of monitoring the heatup of the subsurface during SER; however, the magnitude of the resistivity changes determined was not consistent with the expected change based on prior laboratory measurements of resistivity of limestone as a function of temperature. Based on the limited duration of steam injection during this project, it cannot be determined conclusively that

steam injection would be capable of heating the entire treatment area to the target temperature. However, since the rock chip sampling showed that most of the contaminants were located at the fracture surfaces or within 0.3 meter (1 foot) of the fracture surface, the heat that was injected was concentrated where the contaminants were found. It is possible that adequate treatment might have been achieved even without achieving target temperatures throughout the target zone.

Despite the limited heating that occurred, effluent vapor and water samples showed that after approximately three weeks of operations, the extraction rates started to increase, and they continued to increase for the duration of the project. The highest extraction rates were achieved at the end of the project, after steam injection had ceased and air injection was increased. This is believed to be due to air stripping of VOCs at the higher subsurface temperatures, which carried the vaporized contaminants to extraction wells. Effluent samples showed that more than 7.4 kg (16.2 lbs) of contaminants were recovered during the project, of which 5.0 kg (11.12 lbs) were chlorinated VOCs, 0.55 kg (1.22 lbs) were gasoline range organics (GRO), and 1.77 kg (3.9 lbs) were diesel range organics (DRO). Based on the high concentrations of PCE and DRO in some wells during the last round of sampling, it is believed that NAPL was about to be extracted.

Sampling of the effluent vapor and water streams just prior to discharge showed that the vapor and water treatment systems employed by SteamTech effectively treated these streams to meet discharge limitations. Ground water samples from two angled wells that extended below the treatment area showed that contaminants do not appear to have been moved downward by SER. Ground water samples from two wells just to the north and east of the treatment area showed that contaminants were not moved horizontally into those areas. Evaluation of operations data shows that higher steam injection pressure can be used in competent bedrock than are typically possible in unconsolidated media, and the importance of the co-injection of air and pressure cycling to enhance the transport of mobilized contaminants to extraction wells.

The evolution of the CSM as additional characterization information became available, and after the completion of the steam injection, allowed an evaluation of the importance of different characterization activities to understanding ground water and contaminant transport in fractured rock, and to the design and implementation of the SER system. It was determined that a variety of characterization activities are required to understand the flow system and contaminant distribution sufficiently for remediation system design and operation.

For large, simple-to-moderately complex fractured rock sites, SER may be an efficient and cost effective remediation technology for VOCs. However, for highly complex, low permeability fractured sites with low interconnectivity, such as the Loring Quarry, steam injection may not be the best method for remediation. In order for SER to be successful in such an environment, extensive characterization is needed, and extremely long injection times are likely necessary. Even with long injection times, heat losses may limit the ability to heat the entire target zone. For sites such as this, Thermal Conductive Heating (TCH) or Electrical Resistance Heating (ERH) may be more capable of uniformly heating the target zone, and may be effectively implemented with less characterization, resulting in an overall reduction in remediation costs. Further research is warranted on steam injection remediation in fractured rock in less complex sites, and on the application of ERH and TCH to contaminated fractured rock sites.

Contents

| | |
|--|-------|
| Preface | v |
| Acknowledgments | vi |
| Executive Summary | vii |
| Figures | xiii |
| Tables | xvi |
| Plates | xvii |
| Acronyms and Abbreviations | xviii |
| Chapter 1. Introduction | 1 |
| 1.1. Site Description and History | 2 |
| 1.1.1. Site Description | 2 |
| 1.1.2. Administrative History | 3 |
| 1.1.3. Technology Selection | 3 |
| 1.1.4. Project Structure and Administration | 3 |
| 1.2. Project Chronology | 3 |
| 1.3. Objectives of Research Project | 4 |
| 1.3.1. EPA's SITE Program | 5 |
| 1.3.1.1. Primary Objectives | 5 |
| 1.3.1.2. Secondary Objectives | 6 |
| 1.3.2. Technology Objectives | 7 |
| 1.3.2.1. Detailed Technology Objectives | 7 |
| 1.3.2.2. Supplemental Technology Objectives | 9 |
| Chapter 2. Initial Hydrogeologic Conceptual Site Model | 11 |
| 2.1. Introduction | 11 |
| 2.2. Bedrock Structure | 13 |
| 2.3. Hydraulic Conditions | 15 |
| 2.4. Contaminant Distribution | 16 |
| 2.5. Initial Conceptual Site Model | 17 |
| Chapter 3. General Description of Steam Injection | 19 |
| 3.1. NAPL Source Zones and Plume Longevity | 19 |
| 3.2. Steam Enhanced Remediation Technology Background | 19 |
| 3.3. Thermal Remediation Mechanisms | 20 |
| 3.4. Steam Injection Demonstrations and Remediations in Unconsolidated Media | 21 |
| 3.5. Steam Demonstrations in Fractured Rock | 22 |
| Chapter 4. Characterization for Design and Implementation | 23 |
| 4.1. Characterization Activities | 24 |
| 4.1.1. Drilling Program | 24 |
| 4.1.2. Rock Chip Sampling | 24 |
| 4.1.3. Borehole Geophysics | 34 |
| 4.1.4. Transmissivity Measurements | 36 |
| 4.1.4.1. Method | 36 |
| 4.1.4.2. Discussion of Results | 37 |
| 4.1.5. Deep Monitoring Wells | 47 |

| | | |
|------------|---|-----|
| 4.1.5.1. | Drilling | 47 |
| 4.1.5.2. | Well Installation and Hydraulic Testing | 48 |
| 4.1.6. | Interconnectivity Testing | 50 |
| 4.1.6.1. | Methods | 51 |
| 4.1.6.2. | Results | 52 |
| 4.1.7. | Ground Water Sampling | 53 |
| 4.1.7.1. | Sampling of Treatment Area Boreholes | 54 |
| 4.1.7.2. | Sampling of Deep Wells | 59 |
| 4.1.7.3. | Ground Water Data QC Summary | 61 |
| 4.2. | Pre-Operation Conceptual Model of Site | 61 |
| 4.2.1. | Geology | 62 |
| 4.2.2. | Contaminant Distribution | 62 |
| 4.2.3. | Hydrogeology | 64 |
| Chapter 5. | Well Field, Process, and Subsurface Monitoring Design | 71 |
| 5.1. | Injection and Extraction System (As-Built) | 71 |
| 5.2. | Above-Ground Systems | 76 |
| 5.2.1. | Steam Generation | 76 |
| 5.2.2. | Effluent Extraction and Treatment Systems | 78 |
| 5.2.2.1. | Vapor Extraction and Treatment System | 78 |
| 5.2.2.2. | Water Extraction and Treatment System | 79 |
| 5.3. | Subsurface Monitoring | 79 |
| 5.3.1. | DigiTAM™ Temperature Monitoring System | 79 |
| 5.3.2. | ERT System | 79 |
| 5.4. | Modifications Made During Operations | 81 |
| Chapter 6. | Injection-Extraction Rates and Water-Energy Balances | 83 |
| 6.1. | Injection Rates | 83 |
| 6.1.1. | Steam Injection Rate | 83 |
| 6.1.2. | Air Injection Rates | 85 |
| 6.2. | Extraction Rates | 86 |
| 6.2.1. | Vapor Extraction Rates | 86 |
| 6.2.2. | Ground Water Extraction Rates | 87 |
| 6.3. | Water Balance | 88 |
| 6.3.1. | Methods | 88 |
| 6.3.2. | Results | 89 |
| 6.4. | Energy Balance | 91 |
| 6.4.1. | Methods | 91 |
| 6.4.2. | Results | 91 |
| Chapter 7. | Subsurface Temperature and ERT Monitoring Results | 95 |
| 7.1. | Temperature Monitoring | 95 |
| 7.1.1. | General Trends in Heating | 95 |
| 7.1.2. | Temperature Data Supporting Interconnectivity Testing | 98 |
| 7.1.2.1. | Profiles Showing a Constant Temperature Increase | 99 |
| 7.1.2.2. | Profiles Showing a Post-Retrofit Temperature Increase | 105 |
| 7.1.2.3. | Profiles Showing a Response that Suggests Vertical Heat Migration | 105 |
| 7.1.2.4. | Profiles Showing Evidence of Long-Distance Thermal Migration | 105 |
| 7.1.3. | Post-Steam Injection Temperature Monitoring | 106 |
| 7.1.4. | Post-SER Borehole Investigation | 106 |
| 7.2. | Subsurface ERT Monitoring | 106 |
| Chapter 8. | Effluent Sampling Results | 117 |
| 8.1. | Ground Water and Process Stream Results | 117 |
| 8.1.1. | Extraction Well PID Screening | 117 |
| 8.1.2. | Extraction Well VOC Samples | 119 |
| 8.1.3. | PID Screening of Process Streams | 122 |
| 8.1.4. | Vapor Screening Results (FID) | 123 |
| 8.2. | Contaminant Recovery Rates and Total Contaminants Recovered | 123 |
| 8.2.1. | Vapor Phase Recovery | 123 |

| | |
|---|-----|
| 8.2.2. Aqueous Phase Recovery | 133 |
| 8.2.3. Total Mass Recovered | 139 |
| 8.3. Compliance Monitoring | 139 |
| 8.3.1. Emitted Vapor Concentrations | 139 |
| 8.3.2. Discharged Water Samples | 141 |
| Chapter 9. Post-Treatment Rock and Ground Water Sampling | 143 |
| 9.1. Rock Chip Sampling Results | 143 |
| 9.2. Ground Water Monitoring | 148 |
| 9.2.1. May 2003 Monitoring Round | 154 |
| 9.2.2. October 2003 Monitoring Round | 154 |
| 9.2.3. May 2004 Monitoring Round | 155 |
| 9.2.4. Ground Water QC Summary | 155 |
| 9.2.5. Ground Water Summary | 155 |
| Chapter 10. Discussion and Interpretation | 157 |
| 10.1. Post-Operational Conceptual Model | 157 |
| 10.2. Discussion of Removal Mechanisms | 163 |
| 10.3. Evaluation of Objectives | 164 |
| 10.3.1. Discussion of EPA SITE Program Objectives | 164 |
| 10.3.2. Discussion of Technology Objectives | 167 |
| 10.3.3. Discussion of Additional Technology Objectives | 170 |
| Chapter 11. Conclusions | 173 |
| 11.1. Lessons Learned | 173 |
| 11.1.1. Characterization | 173 |
| 11.1.1.1 Detailed Mapping | 173 |
| 11.1.1.2 Coring | 173 |
| 11.1.1.3 Borehole Geophysics | 174 |
| 11.1.1.4 Acoustic Televiwer (ATV) | 174 |
| 11.1.1.5 MERC Sampling | 174 |
| 11.1.1.6 Discrete Interval Ground Water Sampling | 174 |
| 11.1.1.7 Head Measurements | 174 |
| 11.1.1.8 Discrete Interval Transmissivity Testing | 175 |
| 11.1.1.9 Interconnectivity Testing | 175 |
| 11.1.1.10 Deep Well Ground Water Sampling | 175 |
| 11.1.2. Steam Enhanced Remediation | 176 |
| 11.2. Technology Application | 177 |
| 11.2.1. General Challenges for SER Applications in Fractured Rock | 177 |
| 11.2.2. Recommended Approach for SER Implementation at Fractured Rock Sites | 178 |
| 11.2.3. Amendments and Alternative Approaches | 180 |
| 11.2.4. Conceptual Comparison of SER and TCH/ERH Costs for a Range of Site Complexity | 181 |
| Chapter 12. Recommendations for Future Research Related to Thermal Remediation in Fractured Rock | 183 |
| 12.1. Rock Chip Samples to Determine Contaminant Distribution | 183 |
| 12.2. Monitoring Methods | 183 |
| 12.3. Evaluation of Existing Heat Flow Data | 184 |
| 12.4. Mechanistic Laboratory Studies of Steam Flow in Fractures | 184 |
| 12.5. Mechanistic Studies of TCH and ERH in Rock Settings | 184 |
| 12.6. Effects of SER on the Dissolved Phase Plume | 184 |
| 12.7. Effects of Injection and Extraction on a Larger Area | 185 |
| 12.8. Use of Moveable, Inflatable Packers in Injection Wells | 185 |
| References | 187 |

Appendices (Contained on Accompanying CD)

- A. Cost Summary
- B. Boring Logs
- C. Analytical Data
- D. Borehole Geophysical Data
- E. QA for Single Hole Transmissivity Tests
- F. Interconnectivity Data
- G. USGS Radar Tomography Paper
- H. Journal Articles
- I. Electrical Resistance Tomography Profiles and Temperature Profiles

Figures

| | | |
|-------------------|--|----|
| Figure 1.1.1-1. | Location map for the former Loring Air Force Base and the Quarry site. | 2 |
| Figure 2.1-1. | Aerial view of the Loring Air Force Base Quarry. | 11 |
| Figure 2.1-2. | Results of previous ground water investigations at the Quarry. | 12 |
| Figure 2.2-1. | Bedrock geology of northeastern Aroostook County, Maine. | 13 |
| Figure 2.2-2. | Primary structural features of the Quarry. | 14 |
| Figure 2.2-3. | Diagrammatic cross-sectional representation of the fracturing of the Quarry. | 15 |
| Figure 2.4-1. | Loring Quarry PCE plume map. | 16 |
| Figure 4.0-1. | General site layout developed by SteamTech in April 2001. | 23 |
| Figure 4.1.4.1-1. | Schematic diagram illustrating the packer and standpipe configuration used for measuring transmissivity in the site boreholes. | 36 |
| Figure 4.1.4.2-1. | Location of wells and cross-sections plotted in Figures 4.1.4.2-2 to Figure 4.1.4.2-4. | 45 |
| Figure 4.1.4.2-2. | Transmissivity versus depth profiles for wells along central axis of site. | 46 |
| Figure 4.1.4.2-3. | Transmissivity versus depth profiles for wells in central part of site. | 46 |
| Figure 4.1.4.2-4. | Transmissivity versus depth profiles of wells on northern edge of site. | 47 |
| Figure 4.1.5.1-1. | Location and orientation of the deeper boreholes constructed around the periphery of the steam footprint. | 48 |
| Figure 4.1.5.2-1. | Hydraulic head with respect to elevation in each borehole. | 49 |
| Figure 4.1.5.2-2. | Transmissivity with respect to elevation in each deep borehole. | 50 |
| Figure 4.1.6.1-1. | Schematic diagram of the apparatus used for the pulse interference tests conducted using the slug test format. | 51 |
| Figure 4.1.6.2-1. | The source and observation response for an example pulse interference test. | 52 |
| Figure 4.2.1-1. | Conceptual model of geological structure at Quarry. | 63 |
| Figure 4.2.3-1. | Plan view of the basic interconnections determined for individual well bore pairs. | 66 |
| Figure 4.2.3-2. | Plan view of the injection and extraction well array showing the location of specific cross-sections. | 66 |
| Figure 4.2.3-3. | Interconnection along the northern perimeter of the site. | 67 |
| Figure 4.2.3-4. | Interconnections between I-4 and I-5. | 67 |
| Figure 4.2.3-5. | Profile view of fracture interconnections looking east. | 68 |
| Figure 4.2.3-6. | Fracture interconnections looking towards the northeast. | 69 |
| Figure 4.2.3-7. | Profile view of fracture interconnections looking north. | 69 |
| Figure 4.2.3-8. | Fracture interconnections looking down and towards north-northeast. | 70 |

| | | |
|-------------------|--|-----|
| Figure 4.2.3-9. | Profile view of fracture interconnections looking downwards and towards the northeast. | 70 |
| Figure 5.1-1. | Well field layout. | 71 |
| Figure 5.1-2a. | Injection well design summary. | 73 |
| Figure 5.1-2b. | Extraction well design summary. | 74 |
| Figure 5.1-3. | Site layout, as-built. | 75 |
| Figure 5.2.1-1. | Steam generation and distribution system schematic. | 76 |
| Figure 5.2.2-1. | Extracted vapor and liquid treatment system schematic. | 78 |
| Figure 5.4-1. | Location of the concrete seal placed over the eastern part of the site in mid-October. | 82 |
| Figure 6.1.1-1. | Injection rate for each of the injection wells. | 83 |
| Figure 6.1.1-2. | Cumulative energy amounts injected into each injection well. | 84 |
| Figure 6.1.2-1. | Air injection pressure versus time. | 85 |
| Figure 6.1.2-2. | Air injection rate versus time. | 85 |
| Figure 6.2.1-1. | Extracted vapor flow rate. | 87 |
| Figure 6.2.2-1. | Extracted liquid flow rates for wellfield (calculated for point W-1 based on L-1 and KO-2 data). | 87 |
| Figure 6.2.2-2. | Cumulative water extraction from each of the extraction wells, based on corrected stroke counter measurements. | 88 |
| Figure 6.3.2-1. | Water flow rates for the various injection and extraction streams. | 89 |
| Figure 6.3.2-2. | Cumulative water volumes and balance. | 90 |
| Figure 6.4.2-1. | Enthalpy fluxes for the various streams during operations. | 92 |
| Figure 6.4.2-2. | Energy balance with cumulative energies for the various streams during operations. | 92 |
| Figure 6.4.2-3. | Calculation of average subsurface temperature in the test volume and estimated rock volumes that could be heated to 87 and 100°C. | 93 |
| Figure 7.1.1-1. | Background temperature profiles in site wells. | 95 |
| Figure 7.1.1-2. | Interpreted progression of heating across the site. | 96 |
| Figure 7.1.1-3. | Temperature profiles of wells in the eastern area. | 97 |
| Figure 7.1.1-4. | Temperature profiles of wells in central area showing heat up after October 14. | 98 |
| Figure 7.1.1-5. | Temperature profiles of wells in western area showing heat up after November 19. | 99 |
| Figure 7.1.1-6. | Temperature profiles of well I-8 and boring VEA-7 on southern boundary of site, showing rise in temperature of peripheral boring VEA-7 while adjacent steam injection well I-8 cools. | 100 |
| Figure 7.1.2.1-1. | Wells exhibiting constant temperature increase. | 102 |
| Figure 7.1.2.1-2. | Wells exhibiting post-retrofit temperature increase. | 102 |
| Figure 7.1.2.1-3. | Wells exhibiting evidence of vertical heat migration. | 103 |
| Figure 7.1.2.1-4. | Wells exhibiting long distance temperature response. | 103 |
| Figure 7.1.2.1-5. | Post-injection temperature monitoring profiles. | 104 |
| Figure 7.1.4-1. | Fracture at 23.4 meters (76.9 feet) bgs in BD I-5-6. | 107 |

| | | |
|------------------|---|-----|
| Figure 7.2-1. | Relationship of bulk resistivity to temperature (top) and bulk conductivity to temperature (bottom). | 108 |
| Figure 7.2-2. | Site map, showing location of ERT profiles listed in Table 5.3.2-1. | 109 |
| Figure 7.2-3. | Conductivity profiles of perimeter planes, November 30. | 111 |
| Figure 7.2-4. | Resistivity anomalies interpreted as indicating the passage of heated water across the perimeter of the treatment area. | 112 |
| Figure 7.2-5. | Examples of high conductivity anomalies parallel to VEA borings. | 113 |
| Figure 7.2-6. | Conductivity profiles of interior planes, November 30. | 114 |
| Figure 7.2-7. | Plane TC1-9-4, showing development of conductivity anomalies over time. | 115 |
| Figure 8.1.1-1. | Headspace PID screening data for the first subset of extraction wells. | 118 |
| Figure 8.1.1-2. | Headspace PID screening data for the second subset of extraction wells. | 118 |
| Figure 8.1.2-1. | PCE concentrations in the VOC grab samples from the extraction wells. | 119 |
| Figure 8.1.2-2. | TCE concentrations in the VOC grab samples from the extraction wells. | 120 |
| Figure 8.1.2-3. | Naphthalene concentrations in the VOC grab samples from the extraction wells. | 121 |
| Figure 8.1.2-4. | 1,2,4-Trimethylbenzene concentrations in the VOC grab samples from the extraction wells. | 121 |
| Figure 8.1.3-1. | Results of PID headspace screening of process water samples. | 122 |
| Figure 8.1.4-1. | Results of continuous FID screening of vapors at location V-1 (untreated vapors). | 123 |
| Figure 8.2.1-1. | Vapor phase effluent concentrations over time. | 132 |
| Figure 8.2.1-2. | Vapor phase total VOC daily and cumulative recoveries. | 132 |
| Figure 8.2.2-1. | Aqueous phase effluent concentrations of total solvents, GRO, and DRO. | 137 |
| Figure 8.2.2-2. | Solvent concentrations in the aqueous phase and cumulative recoveries. | 137 |
| Figure 8.2.2-3. | GRO daily and cumulative recovery in the aqueous phase. | 138 |
| Figure 8.2.2-4. | DRO daily and cumulative recovery in the aqueous phase. | 138 |
| Figure 10.1-1. | Schematic cross-sections of site showing those fractures that showed a temperature increase during or after operations. | 158 |
| Figure 10.1-2. | Progressive sequence of heating observed at site, based on first evidence of temperature increase in temperature profiles presented in Appendix I and Plate 7.1.1-1. | 159 |
| Figure 10.1-3a. | PCE concentrations (micrograms/liter) in ground water, April 2002. | 160 |
| Figure 10.1-3b. | PCE concentrations (micrograms/liter) in ground water, May 2003. | 160 |
| Figure 10.1-4. | Interpretation of ground water flow paths under stressed conditions in effect during steam injection operations. | 161 |
| Figure 10.1-5. | Interpretation of ground water flow paths under ambient conditions. | 162 |
| Figure 11.2.4-1. | Sketch of comparative cost of site characterization and treatment costs for SER and TCH/ERH applications to sites with varying complexity. | 182 |

Tables

| | | |
|------------------|--|-----|
| Table 1.2-1. | Project Chronology | 4 |
| Table 1.3.2.1-1. | Primary Technology Objectives (Expanded from Work Plan) | 8 |
| Table 1.3.2.2-1. | Supplemental Technology Objectives (Defined During Course of Demonstration) | 9 |
| Table 4.1.1-1. | Well Drilling Details | 25 |
| Table 4.1.2-1. | Pre-Steam Injection MERC Sample Results | 26 |
| Table 4.1.3-1. | Summary of the Prominent Fractures as Determined from the Borehole Geophysics | 35 |
| Table 4.1.4.2-1. | Summary of Individual Well Transmissivity Profiles | 38 |
| Table 4.1.5.2-1. | Summary of Casing Intervals for SM-1, SM-2, and SM-3 | 49 |
| Table 4.1.6.2-1. | Water Level Measurements Relative to a Datum at 225.6 meters (740 Feet) Above Mean Sea Level | 53 |
| Table 4.1.7.1-1. | Ground Water Sampling Intervals for Treatment Area Wells | 55 |
| Table 4.1.7.1-2. | Pre-Treatment Ground Water Sampling Results from Wells Within the Target Zone | 56 |
| Table 4.1.7.2-1. | Ground Water Sampling Intervals for Deep Wells | 59 |
| Table 4.1.7.2-2. | Pre-Treatment Ground Water Sampling Results from the Deep Boreholes | 60 |
| Table 4.2.3-1. | Wells Within Interconnected Areas | 64 |
| Table 5.2.1-1. | Major Design Parameters and Process Equipment Specifications | 76 |
| Table 5.3.2-1. | List of ERT Profiles | 80 |
| Table 8.2.1-1. | Analytical Results for Vapor Samples from Sample Point V-1 | 125 |
| Table 8.2.2-1. | Analytical Results for Aqueous Phase Samples from Sample Location L-1 | 134 |
| Table 8.2.3-1. | Summary of Contaminant Mass Recovered in Each Phase | 139 |
| Table 8.3.1-1. | Summary of Analytical Data on the Treated Vapor Emitted to the Atmosphere (Sample Location V-4) | 140 |
| Table 8.3.2-1. | Summary of Analytical Data on the Treated Water (Sample Location L-3) | 142 |
| Table 9.1-1. | Post-Treatment Rock Chip Sampling Results | 144 |
| Table 9.2.1-1. | Post-Treatment Ground Water Sampling Results | 148 |

Plates (Contained on Accompanying CD)

- Plate 2.4-2. Cross-sectional representation of the contaminant distribution beneath the upper tier.
- Plate 4.1.2-1. PCE concentrations in rock chip samples.
- Plate 7.1.1-1. Temperature profiles during steam injection.
- Plate 7.1.1-2. Temperature profiles after steam injection.
- Plate 8.1.2-1. Effluent concentrations from each of the extraction wells.
- Plate 9.2.4-1. Summary of total VOC concentrations in ground water over the life of the project in wells used for extraction.

Acronyms and Abbreviations

| | |
|--------|---|
| AFB | Air Force Base |
| ALT | Advanced Logic Technologies |
| ARAR | Applicable or Relevant and Appropriate Standard |
| atm | atmosphere |
| ATV | Acoustic Televiewer |
| BCT | below casing top |
| BD | back drill |
| bgs | below ground surface |
| BIPS | Borehole Image Profiling System |
| BRAC | Base Realignment and Closure |
| BTEX | Benzene, toluene, ethyl benzene, and xylene |
| Btu | British thermal unit |
| CERCLA | Comprehensive Environmental Response, Compensation, and Liability Act |
| COC | Contaminant of Concern |
| CSM | Conceptual Site Model |
| CVOC | Chlorinated Volatile Organic Compound |
| DCA | Dichloroethane |
| DCE | Dichloroethylene |
| DEP | Department of Environmental Protection |
| DNAPL | Dense Non-Aqueous Phase Liquid |
| DRO | Diesel Range Organics |
| EM | Electromagnetic |
| EPA | Environmental Protection Agency |
| ER | Electrical resistivity |
| ERH | Electrical Resistance Heating |
| ERT | Electrical Resistance Tomography |
| EX | Extraction |
| FID | Flame Ionization Detector |
| FS | Feasibility Study |
| ft | feet |
| GAC | Granular activated carbon |

| | |
|--------|--|
| gpm | gallons per minute |
| GRO | Gasoline Range Organics |
| HLA | Harding Lawson Associates |
| HPFM | Heat pulse flow meter |
| I | Injection |
| kg | kilograms |
| kJ/hr | kiloJoules per hour |
| kPa | kiloPascals |
| kWh | kiloWatt hours |
| lbs | pounds |
| LNAPL | Light Non-Aqueous Phase Liquid |
| lpm | liters per minute |
| m | meters |
| MCL | Maximum Contamination Level |
| MEDEP | Maine Department of Environmental Protection |
| MERC | Methanol extracted rock chip |
| mg/kg | milligrams per kilogram |
| mg/l | milligrams per liter |
| MS/MSD | Matrix spike/matrix spike duplicate |
| msl | mean sea level |
| NAPL | Non-Aqueous Phase Liquid |
| NFCS | Nonfracture control sample |
| NRMRL | National Risk Management Research Laboratory |
| ORD | Office of Research and Development |
| OTV | Optical televiewer |
| PCE | Tetrachloroethylene |
| PID | Photo-Ionization Detector |
| ppmv | parts per million volume |
| QAPP | Quality Assurance Project Plan |
| QC | Quality Control |
| RFP | Request for Proposals |
| RI | Remedial Investigation |
| ROD | Record of Decision |
| RPD | Relative Percent Difference |
| SARA | Superfund Amendments and Reauthorization Act of 1986 |
| scfm | standard cubic foot per minute |
| scmm | standard cubic meter per minute |
| SER | Steam Enhanced Remediation |

| | |
|-------|---|
| SITE | Superfund Innovative Technology Evaluation |
| SOP | Standard Operating Procedure |
| TC | Thermocouple |
| TCE | Trichloroethylene |
| TCH | Thermal Conduction Heating |
| TDS | Total Dissolved Solids |
| TI | Technical Impracticability |
| TIO | Technology Innovation Office |
| USAF | United States Air Force |
| USEPA | United States Environmental Protection Agency |
| USGS | United States Geological Survey |
| VEA | Vertical Electrode Array |
| VLf | Very low frequency |
| VOA | Volatile Organics Analysis |
| VOC | Volatile Organic Compound |